Putting Things in Order

> The periodic table is arguably the most important concept in chemistry, both in principle and in practice.... It is a remarkable demonstration of the fact that the chemical elements are not a random clutter of entities but instead display trends and lie together in families.
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> —P. W. Atkins (1940–), British chemistry professor, *The Periodic Kingdom*

> Mendeleyev was aware of the significance of his search. This could be the first step towards uncovering, in future centuries, the ultimate secret of matter, the pattern upon which life itself was based, and perhaps even the origins of the universe.
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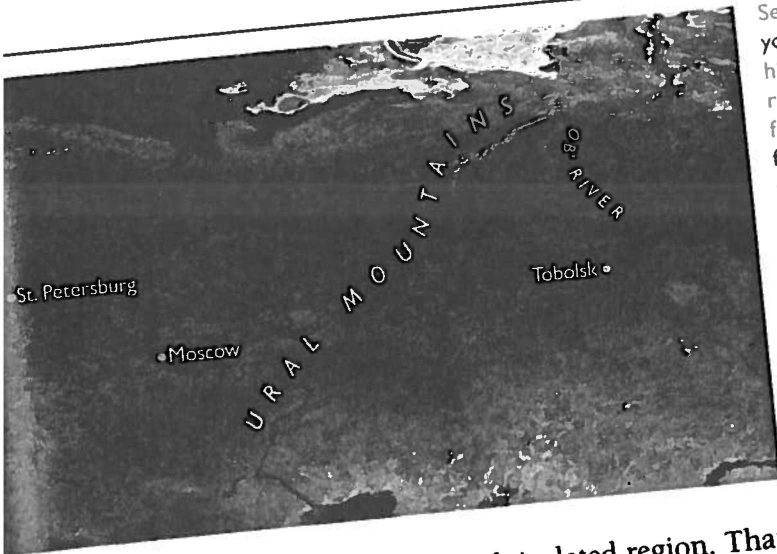
> —Paul Strathern (1940–), British science writer, *Mendeleyev's Dream: The Quest for the Elements*

Scientists don't believe in magic—reason and proofs define science—and yet white-bearded Dmitri Ivanovich Mendeleyev (men-duh-LAY-ef), seemed to bring the magic of prophecy to science. He predicted that certain unknown elements would be found, he described their characteristics, and then he sat back and waited. Most people laughed. When the first of his predicted elements turned up, they explained it as coincidence. But when another was found, and another—well, the whole world soon paid attention.

Who is Dmitri Mendeleyev?

In Tobolsk, the home town of Dmitri Mendeleyev, stands a gold-domed Orthodox Christian church

He begins life as the youngest son in a family of 14 children. His father is a high school principal. They live in Tobolsk, a small town in Siberia. His mother's father had been



Seeking a better education, young Dmitri, his mother, and his sister walked and caught rides on horse carts to travel from Siberia to Moscow and, finally, to St. Petersburg. His mother and sister soon died, and he caught tuberculosis (a serious lung disease), but Dmitri threw himself into learning.

ne of the Russian pioneers in that cold, isolated region. That randfather published the first newspaper in Siberia, the *rtysh*, and he established a glass factory in Tobolsk.

When Dmitri is very young, his father goes blind. Dmitri's mother—known for her beauty and strong-mindedness—reopens the glass factory, builds a church and school for its workers, and supports the family. When Dmitri is 13, his father dies.

Siberia is where the Russian leaders send their political prisoners—especially those who protest against the czar's rule. It seems like the end of the world to most who are forced to stay there. One of Dmitri's sisters marries an exile. That is lucky for Dmitri: His brother-in-law is a scientist who answers the boy's questions and teaches him about the world of science.

When a fire destroys the glass factory, Dmitri, his mother, and his youngest sister leave Siberia and head west to Moscow. Dmitri has done poorly in school in Tobolsk; his mother is determined that her son get a good education. They make the 2,000-kilometer (1,250-mile) journey by hitching rides on horse-drawn wagons.

In Moscow the schools won't recognize his Siberian qualifications. They turn him down. The trio moves on, this time to St. Petersburg, where his mom has a friend. In bureaucratic Russia, knowing someone helps. He is admitted

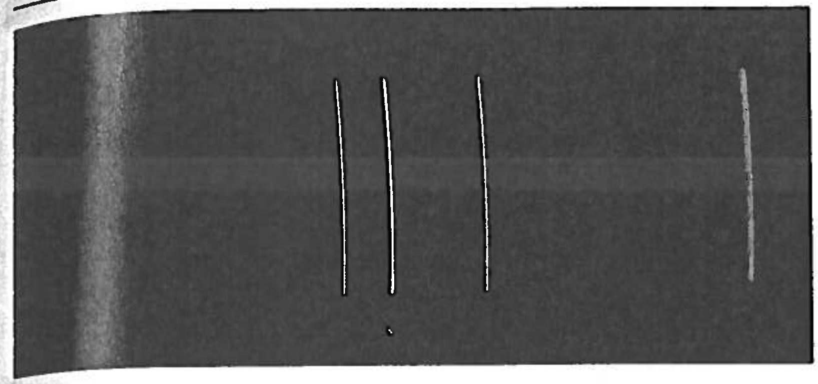
to the Central Pedagogical Institute (a fine school). His mother tells him, "insist on work and not on words." And, "patiently seek divine and scientific truth." Ten weeks later she is dead. Her words will remain his lifelong inspiration.

But things don't get easy for him. His sister dies, and he is diagnosed with tuberculosis. No one expects him to live. Dmitri moves into a hospital and goes to classes from there. Actually that gives him some independence. The orphan becomes a kind of mascot at school and at the hospital. He's given freedom to study and experiment as he wishes. His mind catches fire, and he is soon doing original scientific research. In 1855, he graduates at the top of his class. That leads to opportunities. (And he seems to have recovered his health.) His friend Aleksandr Borodin, a first-rate chemist and a famous composer, encourages him to go to France for graduate work. There he has the good luck to study with a fine experimental chemist. That training will serve him well.

Robert Bunsen (center) poses with his friends in chemistry, Gustav Kirchhoff and Henry Roscoe. Besides the famous Bunsen burner, he invented the Bunsen ice calorimeter to measure the amount of thermal energy in a substance.

From France, he heads for Germany, where (more luck) he works with Robert Bunsen (a great teacher and the inventor of the Bunsen burner, still found in today's science labs). Bunsen is using a prism to split light into a color spectrum, as Newton did, but he takes it one step further. He heats elements with his burner, refracts the light they give off, and finds that each produces a unique spectrum—a color "fingerprint" that can be used to identify the elements. (This is the science of spectroscopy.) Dmitri Mendeleyev has put himself at a center of cutting-edge science.

But chemistry is in a confused state: a simple compound may be written 10 different ways by 10 different chemists. Coordination is close to impossible. When Mendeleyev studies John Dalton's atomic weights—numbers that



Only one element gives off this pattern of electromagnetic (EM) energy: cadmium (Cd), a soft and silvery transition metal similar to zinc, yet rarer. The pattern is a record of which wavelengths of radiation a cadmium atom absorbs and emits and which ones it doesn't. A spectrometer is an instrument that collects and measures the emitted radiation.

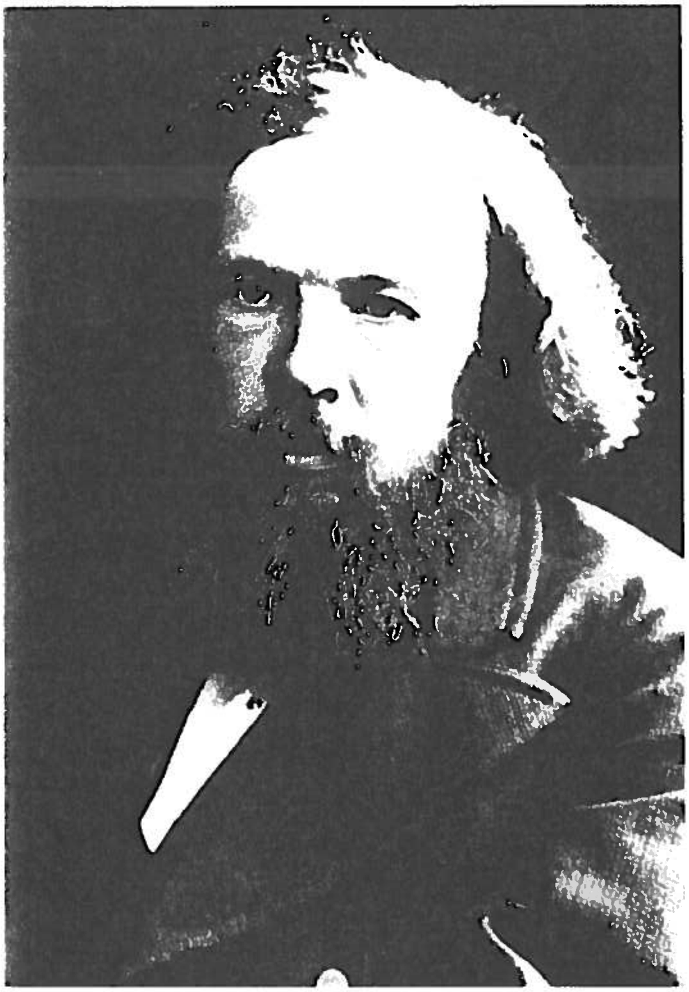
describe the mass of an atom in any given element—he realizes that hardly anyone agrees even on those weights. And Avogadro's ideas about atoms and molecules are mostly forgotten.

In 1860, the First International Chemical Congress is called to try to clear up the confusion. It is held in the little German town of Karlsruhe. The conference's goal is to standardize the atomic and molecular masses that are being used by chemists around the world. Friedrich Kekulé is the man who initiates the meeting.

Mendeleyev attends. He is awed by an Italian scientist who has discovered Avogadro's work and is bursting to tell his fellow scientists about it. (Avogadro had died four years earlier.) The Italian, Stanislao Cannizzaro, makes clear the important difference between atoms and molecules and explains how to use Avogadro's Law. He even passes out copies of a pamphlet he has written on the

"Bunsen, I must tell you how excellent your study of chemical spectroscopy is, as is your pioneer work in photochemistry—but what really impresses me is that cute little burner you've come up with."

In 1860, many leading chemists still thought the formula for water was HO (not H_2O)—just as John Dalton had six decades earlier. Hydrogen atoms naturally occur in bonded pairs (H_2). But the chemists figured that two like atoms, as with two like electric charges, could only repulse each other. Resistance to the idea of diatomic molecules was what begged the central question of the Karlsruhe conference: What is an atom and what is a molecule?



subject. Cannizzaro is the talk of the Karlsruhe conference. After that, chemists begin to agree on formulas and on atomic weights. (It's the nineteenth century, and atomic masses are still called atomic weights.)

The next year, 1861, Mendeleyev is back in Russia as an instructor at St. Petersburg University. Tall and blue-eyed, he is an independent sort, radical, sometimes bad tempered, almost always outspoken. He is identified by his long beard and flowing hair; once a year (in the spring) a sheepherder cuts those locks with sheepshears. To a visiting Scotsman, Mendeleyev is "a peculiar foreigner, every hair of whose head acted in independence of every other."

To those who know his work, he is a genius. Mendeleyev's passion for his subject and his no-nonsense style inspires students; they come from around the world to study with him. One of those students, Prince Kropotkin (a future anarchist leader) later remembered this: "The hall was always crowded with something like two hundred students...but for the few of us who could [understand] it was a stimulant to the intellect and a lesson in scientific thinking which...left deep traces."

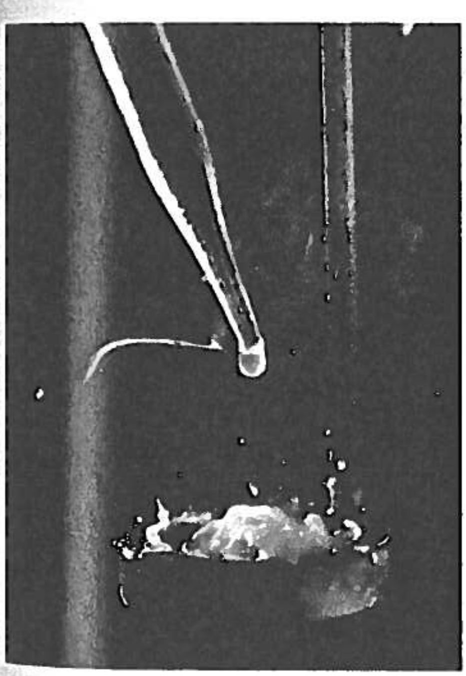
In 1869, Mendeleyev is a 35-year-old chemistry professor with a problem that many teachers face. There isn't a good textbook to use with his students. So he decides to write one. But he doesn't know what order to use when dealing with the elements. He begins by writing about elements that are

clearly linked—like the halogens (fluorine, chlorine, bromine, and iodine), which combine readily with sodium and potassium to make salts (the best known compound being sodium chloride, or table salt). Next, he describes the elements sodium and potassium. And then he hits a wall—he can't find a clear and logical choice for the next group of elements. He believes they must fall into groups, but how?

Mendeleyev is struggling with a predicament that is haunting chemistry: Elements, which are basic to science, seem to have no coherent order. By 1869, 63 elements have been identified. They range from gold and silver (known to the ancients) to rubidium (found in 1861 by Robert Bunsen and Gustav Kirchhoff).

If there is a unifying pattern, it is elusive. Mendeleyev is sure that there is one. So are others. It's a mystery crying to be solved.

Clearly, atomic weight is important. Each of those 63 elements has atoms with a unique mass; it is the one property that is distinctive about every element. Mendeleyev knows that has to be a key in any blueprint. And there must be an explanation as to why some elements share properties (and some don't).



Dmitri searches for clues. He lists the elements by their atomic weight and he also lists them by other characteristics: specific gravity, specific heat, density, state of the element at room temperature (solid, liquid, gas), valence (ability to combine with other atoms), and so on. But one list doesn't seem to relate to the other.

HALOGEN is from the Greek *halos*, meaning "salt."

Rubidium (as in *ruby*, named for the deep-red line in its spectrum) is a rare metal that violently bursts into flames in water and burns up when exposed to air. Bizarre as this sounds, it can safely be stored in kerosene.

Sodium, an alkali metal, is too chemically active to exist in its pure state near liquid or atmospheric water. Still, it's the sixth most abundant element in the Earth's crust and found in many useful chemical compounds. In its pure form, sodium is a silvery metal light enough to float on water, but it's so reactive that, like rubidium, it sizzles, bubbles, and burns when mixed with air or water (as at left).

SPECIFIC GRAVITY is the density of a substance compared to the density of water (1 gram per cubic centimeter). SPECIFIC HEAT is the heat needed to raise or lower 1 gram of a substance 1°C.

Mendeleyev sits at his desk under portraits of Newton, Descartes, and Galileo. For three days in February of 1869, he thinks about nothing else. He is expected to speak at a meeting of cheese makers, and a horse and carriage wait outside his door, but he is obsessed with this problem. He sees it as the most important question in the science of his day. "The edifice of science requires not only material, but also a plan," he says.

Lying on his desk is a letter from the cheese makers with an agenda for his visit. He drinks his morning tea and jots some notes on the back of the letter (the letter still exists with a ring from the teacup). He puts a few elements with similar properties on a horizontal line, including their atomic weights. Those weights vary widely. He sees no sense in them. On a second line, under the first, he lists a different group of elements and their atomic weights. Under that he puts a third group. Then his eye takes him vertically, straight down instead of across. Looked at this way, the weights, for no reason he can imagine, do seem to follow a pattern. Mendeleyev tells the driver of the carriage to leave. The cheese makers will be disappointed.

Mendeleyev, who often plays solitaire, now writes the atomic weights of all the elements on white cards—one element with its atomic weight on each card. He also puts properties of elements on the cards. Then he plays around with the cards, arranging them in rows and columns. He pins them to the laboratory wall and stares. He knows he is close, but he still can't quite get it.

Exhausted, he puts his bushy head on his hands and falls asleep at his desk. Then, in his words, "I saw in a dream a table where all the elements fell into place as required. Awakening, I immediately wrote it down on a piece of paper."

He draws a large rectangle with vertical columns and horizontal rows. In the columns, he lists the elements according to atomic weight—from light to heavy. In the rows, he lines up elements with similar chemical properties. There's a pattern! Reading from left to right across each row, the atomic weights increase by regular amounts. In a few places,

When Mendeleyev arranged the known 63 elements by atomic weight, they went from hydrogen (1), to lead (207). Today, hydrogen is still first, but lead is atomic number 82 out of 92 natural elements. By classifying chemicals, the periodic table not only brought order to chemistry, it allowed for predictions.

RUFFLING FEATHERS

Dmitri Mendeleyev was known as an expert on oil and chemicals. In 1876 he was invited to the United States, where he suggested that oil companies attempt to be more efficient rather than just keep looking for more sources of oil. Some experts are still making that suggestion.

A radical in his political beliefs, Mendeleyev allowed women into his lectures (although he wasn't so radical that he believed they are equal to men). He divorced and remarried, which was not approved of in czarist Russia.

Then, in 1890, he endorsed a petition to the Russian czar protesting his university's poor treatment of students. That was a mistake. The czar was a dictator; he didn't like protests. Mendeleyev was forced to resign and was never again allowed to hold a university job. No matter. The czar became a side note to history; Mendeleyev, a star.

where the pattern doesn't quite work, he has the imagination to place question marks. Mendeleyev sees his grid as a kind of jigsaw puzzle; he believes that missing elements will be found to fill the gaps. He calls what he draws a "periodic table"; he has taken chemistry's alphabet—the atoms of elements—and arranged them into words, sentences, and paragraphs.

To his critics, it all sounds like Russian mysticism. But when the elements gallium (now atomic number 31), scandium (21), and germanium (32) are discovered in 1875, 1879, and 1886 and fill spaces in the periodic table and have the properties Mendeleyev predicted, he becomes world famous.